REPORT DOCUMENTATION PAGE	Form Approved OMB NO. 0704-0188

1. REPORT DATE (DD-MM-YYYY)	2. REPORT TYPE	3. DATES COVERED (From - To)
22-12-2012	Final Report	16-Sep-2008 - 15-Sep-2012

4. TITLE AND SUBTITLE	
Networking Cognitive Radios for Tactical Communications	5a. CONTRACT NUMBER W911NF-08-1-0467
	5b. GRANT NUMBER
	5c. PROGRAM ELEMENT NUMBER 611102
6. AUTHORS Qing Zhao	5d. PROJECT NUMBER
	5e. TASK NUMBER
	5f. WORK UNIT NUMBER

7. PERFORMING ORGANIZATION NAMES AND ADDRESSES	8. PERFORMING ORGANIZATION REPORT NUMBER
University of California - Davis Sponsored Programs 118 Everson Hall Davis, CA 95616 -8671	
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES) U.S. Army Research Office P.O. Box 12211 Research Triangle Park, NC 27709-2211	10. SPONSOR/MONITOR'S ACRONYM(S) ARO 11. SPONSOR/MONITOR'S REPORT NUMBER(S) 54188-NS.29

12. DISTRIBUTION AVAILIBILITY STATEMENT

Approved for Public Release; Distribution Unlimited

13. SUPPLEMENTARY NOTES

The views, opinions and/or findings contained in this report are those of the author(s) and should not contrued as an official Department of the Army position, policy or decision, unless so designated by other documentation.

14. ABSTRACT

This research aims to develop fundamental theories and practical protocols for tactical communication networks of cognitive radios. It focuses on three key areas of cognitive networking: (i) opportunity sensing and cognition; (ii) opportunity tracking and exploitation; and (iii) cognitive networking. We have successfully completed this project. Below we highlight a few most important results obtained under this project. In the area of opportunity sensing, our work on quickest opportunity detection is the first that exploits the presence of multiple channels and the heavy-tail

15. SUBJECT TERMS

Cognitive radio, dynamic spectrum access, coexisting networks

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	15. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT	b. ABSTRACT	c. THIS PAGE			Qing Zhao
UU	UU	UU	UU		19b. TELEPHONE NUMBER 530-752-7390

Standard Form 298 (Rev 8/98)
Prescribed by ANSI Std. Z39.18

Report Title

Networking Cognitive Radios for Tactical Communications

ABSTRACT

This research aims to develop fundamental theories and practical protocols for tactical communication networks of cognitive radios. It focuses on three key areas of cognitive networking: (i) opportunity sensing and cognition; (ii) opportunity tracking and exploitation; and (iii) cognitive networking. We have successfully completed this project. Below we highlight a few most important results obtained under this project. In the area of opportunity sensing, our work on quickest opportunity detection is the first that exploits the presence of multiple channels and the heavy-tail distribution of the connection time in opportunity detection. It gives a fresh twist to the classic problem of quickest change detection in a single stochastic process. In the area of opportunity tracking and exploitation, we have developed low-complexity yet optimal strategies that are robust to model mismatch and variations and capable of tracking fast time-varying spectrum opportunities. Furthermore, they are capable of handling primary systems that are asynchronous and unslotted with general traffic model. In the area of cognitive networking, we obtained the first set of results on analyzing the connectivity and multi-hop delay of heterogeneous networks. We also developed online distributed learning algorithms for cognitive networking under unknown and dynamic models of the coexisting primary systems.

Enter List of papers submitted or published that acknowledge ARO support from the start of the project to the date of this printing. List the papers, including journal references, in the following categories:

(a) Papers published in peer-reviewed journals (N/A for none)

Received		Paper
02/13/2011	1.00	S.H. Ahmad, M. Liu, T. Javidi, Q. Zhao, B. Krishnamachari. Optimality of Myopic Sensing in Multi-Channel Opportunistic Access, IEEE Transactions in Information Theory, (09 2009): . doi:
02/13/2011	2.00	X. Xiao, K. Liu, Q. Zhao. Opportunistic Spectrum Access in Self Similar Primary Traffic, EURASIP Journal on Advances in Signal Processing, (07 2009): . doi:
02/13/2011	3.00	W. Ren, Q. Zhao, A. Swami. Power Control in Cognitive Radio Networks: How to Cross a Multi-Lane Highway, IEEE Journal Selected Areas in Communication, (09 2009): . doi:
02/13/2011	4.00	K. Liu, Q. Zhao, B. Krishnamachari. Dynamic Multichannel Access with Imperfect Channel State Detection, IEEE Transactions on Signal Processing, (05 2010): . doi:
02/13/2011	5.00	K. Liu, Q. Zhao. Indexability of Restless Bandit Problems and Optimality of Whittle Index for Dynamic Multichannel Access, IEEE Transactions in Information Theory, (11 2010): . doi:
02/13/2011	6.00	Q. Zhao, J. Ye. Quickest Detection in Multiple On-Off Processes, IEEE Transactions on Signal Processing, (12 2010): . doi:
05/26/2012	7.00	Wei Ren, Qing Zhao, Ananthram Swami. Connectivity of Heterogeneous Wireless Networks, IEEE Transactions on Information Theory, (07 2011): 4315. doi:
05/26/2012	8.00	Pouya Tehrani, Keqin Liu, Qing Zhao. Opportunistic spectrumaccessinunslottedprimary systems, Journal of the Franklin Institute, (03 2012): 985. doi:
12/22/2012	26.00	Keqin Liu, Qing Zhao. Cooperative Game in Dynamic Spectrum Access with Unknown Model and Imperfect Sensing, IEEE Transactions on Wireless Communications, (04 2012): 1596. doi:
TOTAL:		**9**

Number of Papers published in peer-reviewed journals:

(b) Papers published in non-peer-reviewed journals (N/A for none)

Received	Paper

TOTAL:

Number of Papers published in non peer-reviewed journals:

(c) Presentations

Number of Presentations: 0.00

Non Peer-Reviewed Conference Proceeding publications (other than abstracts):

Received		Paper
12/22/2012	27.00	Keqin Liu, Qing Zhao. Online Learning for Stochastic Linear Optimization Problems, Information Theory and Applications Workshop (ITA). 2012/02/07 03:00:00, . : ,

TOTAL: **1**

Number of Non Peer-Reviewed Conference Proceeding publications (other than abstracts):

Peer-Reviewed Conference Proceeding publications (other than abstracts):

Received		Paper
05/26/2012	9.00	Qing Zhao, Jia Ye. Quickest Change Detection in Multiple On-Off Processes, IEEE International Conference on Acoustics, Speech, and Signal Processing (ICASSP). 2009/04/19 04:00:00, . : ,
05/26/2012	10.00	Wei Ren, Qing Zhao, Ananthram Swami. Connectivity of Cognitive Radio Networks: Proximity vs. Opportunity, ACM MobiCom Workshop on Cognitive Radio Networks. 2009/09/20 04:00:00, . : ,
05/26/2012	11.00	Keqin Liu, Qing Zhao. On the Myopic Policy for a Class of Restless Bandit Problems with Applications in Dynamic Multichannel Access, IEEE Conference on Decision and Control (CDC). 2009/12/16 03:00:00, . : ,
05/26/2012	12.00	Jia Ye, Qing Zhao. Quickest Change Detection in Multiple On-Off Processes: Switching with Memory, Allerton Conference on Communications, Control, and Computing. 2009/09/30 04:00:00, . : ,
05/26/2012	13.00	Wei Ren, Xiangyang Xiao, Qing Zhao. Minimum-Energy Multicast Tree inCognitive Radio Networks, IEEE Asilomar Conference on Signals, Systems, and Computers. 2009/11/01 03:00:00, . : ,
05/26/2012	14.00	Changmian Wang□, Bhaskar Krishnamachari, Qing Zhao, Geir E. Øien. Performance of Round Robin Policies for DynamicMultichannel Access, Information Theory and Applications Workshop. 2010/01/31 03:00:00, . : ,
05/26/2012	15.00	Keqin Liu, Qing Zhao, Bhaskar Krishnamachari. Decentralized Multi-Armed Bandit with Imperfect Observations, Allerton Conference on Communications, Control, and Computing. 2009/09/29 04:00:00, . : ,
05/26/2012	16.00	Keqin Liu, Qing Zhao. Learning from Collisions in Cognitive Radio Networks: Time Division Fair Sharing Without Pre-Agreement, IEEE Military Communication Conference (MILCOM). 2010/10/31 04:00:00, . : ,
05/26/2012	17.00	Pouya Tehrani, Qing Zhao. Multichannel Scheduling and Its Connection to Queueing Network Control Problem, IEEE Military Communication Conference (MILCOM). 2010/10/31 04:00:00, . : ,
05/26/2012	18.00	Pouya Tehrani, Lang Tong, Qing Zhao. Asymptotically Efficient Multi-Channel Estimation for Opportunistic Spectrum Access, IEEE International Workshop on Signal Processing Advances in Wireless Communications (SPAWC). 2011/06/26 04:00:00, . : ,
05/26/2012	19.00	Keqin Liu, Qing Zhao, Bhaskar Krishnamachari. Distributed Learning under Imperfect Sensing in Cognitive Radio Networks, IEEE Asilomar Conference on Signals, Systems, and Computers. 2010/11/07 03:00:00, . : ,
05/26/2012	20.00	Haoyang Liu, Keqin Liu, Qing Zhao. Learning and Sharing in A Changing World: Non-Bayesian Restless Bandit with Multiple Players, Information Theory and Applications Workshop. 2011/02/06 03:00:00, . : ,
05/26/2012	21.00	Haoyang Liu, Keqin Liu, Qing Zhao. Logarithmic Weak Regret of Non-Bayesian Restless Multi-Armed Bandit, IEEE International Conference on Acoustics, Speech, and Signal Processing (ICASSP). 2011/05/22 04:00:00, . : ,

05/26/2012 22.00 Wenhan Dai, Yi Gai , Bhaskar Krishnamachari, Qing Zhao. The Non-Bayesian Restless Multi-Armed Bandit: A Case of Near-Logarithmic Regret,
IEEE International Conference on Acoustics, Speech, and Signal Processing (ICASSP). 2011/05/22 04:00:00, . : ,

05/30/2012 25.00 Hua Liu, Longbo Huang, Bhaskar Krishnamachari, Qing Zhao. A Negotiation Game for Multichannel Access in Cognitive Radio Networks,
The Fourth International Wireless Internet Conference . 2008/11/17 00:00:00, . : ,

12/22/2012 28.00 Keqin Liu, Qing Zhao. Adaptive Shortest-Path Routing under Unknown and Stochastically Varying Link States,
Proc. of the 10th International Symposium on Modeling and Optimization in Mobile, Ad Hoc, and Wireless Networks (WiOpt). 2012/05/15 04:00:00, . : ,

TOTAL: **16**

Number of Peer-Reviewed Conference Proceeding publications (other than abstracts):

(d) Manuscripts

Received Paper

05/26/2012 24.00 Wei Ren, Qing Zhao, Ananthram Swami. Temporal Traffic Dynamics Improve the Connectivity of Ad Hoc Cognitive Radio Networks,
IEEE/ACM Transactions on Networking (07 2011)

TOTAL: **1**

Number of Manuscripts:

Books

Received Paper

TOTAL:

Patents Submitted

Patents Awarded

Awards

1. The PI was awarded the 2010 IEEE Signal Processing Magazine Best Paper Award for her paper co-authored with Brian M. Sadler of
ARL entitled "A Survey of Dynamic Spectrum Access", published in the Vol. 24, No. 3, May 2007 issue.

2. The PI was named UC Davis Chancellor's Fellow in 2010.

3. The PI was the TPC Chair of Cognitive Radio Networks Symposium of GLOBECOM 2011.

4. The PI was the tutorial speaker on cognitive radio networks at SPCOM 2012.

5. The PI was a plenary speaker at the 11th IEEE Workshop on Signal Processing Advances in Wireless Communications, June, 2010.

6. The PI was an invited overview lecture speaker on dynamic spectrum access at the 11th Annual International Symposium on Advanced Radio Technologies (ISART), 2010.

7. The PI was a tutorial speaker on dynamic spectrum access and cognitive radio at the IEEE International Conference on Communications (ICC), May, 2010.

8. The PI was an invited overview talk speaker for Thematic Symposium on Signal Processing for 4G Wireless at ICASSP 2009 where she presented an overview on cognitive radio for dynamic spectrum access.

9. The PI gave tutorials on cognitive radio for dynamic spectrum access at MILCOM 2008 and DySPAN 2008.

10. The PI is the organizer and the chair of a workshop on cognitive radio networks (CoRoNet) at ACM MobiCom 2009.

11. A Ph.D. student (Keqin Liu) supported by this project received the 2012 Zuhair A. Munir Award for Best Doctoral Dissertation at UC Davis.

Graduate Students

NAME	PERCENT_SUPPORTED	Discipline
Keqin Liu	0.25	
Pouya Tehrani	0.50	
Wei Ren	0.20	
Jia Ye	0.20	
Haoyang Liu	0.10	
FTE Equivalent:	**1.25**	
Total Number:	**5**	

Names of Post Doctorates

NAME	PERCENT_SUPPORTED
Keqin Liu	0.50
FTE Equivalent:	**0.50**
Total Number:	**1**

Names of Faculty Supported

NAME	PERCENT_SUPPORTED	National Academy Member
Qing Zhao	0.20	
FTE Equivalent:	**0.20**	
Total Number:	**1**	

Names of Under Graduate students supported

NAME	PERCENT_SUPPORTED
FTE Equivalent:	
Total Number:	

Student Metrics

This section only applies to graduating undergraduates supported by this agreement in this reporting period

The number of undergraduates funded by this agreement who graduated during this period: 0.00

The number of undergraduates funded by this agreement who graduated during this period with a degree in science, mathematics, engineering, or technology fields:...... 0.00

The number of undergraduates funded by your agreement who graduated during this period and will continue to pursue a graduate or Ph.D. degree in science, mathematics, engineering, or technology fields:...... 0.00

Number of graduating undergraduates who achieved a 3.5 GPA to 4.0 (4.0 max scale):...... 0.00

Number of graduating undergraduates funded by a DoD funded Center of Excellence grant for Education, Research and Engineering:...... 0.00

The number of undergraduates funded by your agreement who graduated during this period and intend to work for the Department of Defense 0.00

The number of undergraduates funded by your agreement who graduated during this period and will receive scholarships or fellowships for further studies in science, mathematics, engineering or technology fields:...... 0.00

Names of Personnel receiving masters degrees

NAME	
Jia Ye	
Haoyang Liu	
Total Number:	**2**

Names of personnel receiving PHDs

NAME	
Keqin Liu	
Wei Ren	
Total Number:	**2**

Names of other research staff

NAME	PERCENT_SUPPORTED
FTE Equivalent:	
Total Number:	

Sub Contractors (DD882)

Inventions (DD882)

Scientific Progress

See Attachment.

Technology Transfer

Scientific Progress

This research aims to develop fundamental theories and practical protocols for tactical communication networks of cognitive radios. It focuses on three key areas of cognitive networking: (i) opportunity sensing and cognition; (ii) opportunity tracking and exploitation; and (iii) cognitive networking. In the following, we summarize our major scientific findings in each of these three research areas.

1 Opportunity Sensing and Cognition

Under this research topic, our focus is on the quickest detection of spectrum opportunities under reliability constraints. This work is the first that exploits the presence of multiple channels and the heavy-tail distribution of the connection time in opportunity detection. It gives a fresh twist to the classic problem of quickest change detection in a single stochastic process.

We investigate quickest detection of spectrum opportunities in multiple channels where the transmissions of primary users are unslotted and asynchronous. We have formulated this problem as quickest detection of idle/off periods in multiple on-off processes. We show that this problem presents a fresh twist to the classic signal processing problem of quickest change detection that considers only one stochastic process. In particular, we demonstrate that the key to quickest change detection in multiple processes is to abandon the current process when its state is unlikely to change in the near future (as indicated by the measurements obtained so far) and seek opportunities in a new process. Such a channel switching strategy is especially crucial to quickest opportunity detection when the connection time (channel busy duration) of the primary network has a heavy tail distribution.

In [1–3], we have established a Bayesian formulation of quickest detection of spectrum opportunities in multiple unslotted and asynchronous channels within a decision-theoretic framework. Based on this Bayesian formulation, we have established the basic structures of the optimal detection and switching rules in both the infinite and the finite regimes in terms of the number of on-off processes.

In the infinite case, we consider a large number of homogeneous independent on-off processes and the user always switches to a new process should it decide to abandon the current one. We formulate the problem as a Partially Observable Markov Decision Process (POMDP). While POMDPs are PSAPCE-hard in general, we show that for the problem at hand, the optimal decision rule has a simple threshold structure when the busy and idle times of the on-off processes obey (potentially different) geometric/exponential distributions. The threshold structure is with respect to the *posterior* probability that the process currently being observed is idle at the current time (given the entire observation history).

In the finite case, we address quickest detection with memory: switching back to a previously visited process is allowed, and measurements obtained during previous visits are taken into account in decision making. We show that this freedom of switching with memory significantly complicates the problem. The resulting POMDP changes from a one-dimensional problem to an N-dimensional problem, where N is the number of on-off processes. Our objective is to establish the basic structure of the optimal decision rule and develop low-complexity policies with strong performance. In particular, we show that the optimal action of declaring always occurs in the process with the largest posterior probability of being in the idle state. The monotonicity of the detection threshold is also established. Based on the basic structure of the optimal policy, we propose a low-complexity threshold policy. Specifically, under the proposed policy, the user always observes the process with the largest posterior probability of being idle and declares when the largest posterior probability exceeds the detection threshold. The near optimal performance of this threshold policy is demonstrated by a comparison with a full-sensing scheme which defines an upper bound on the optimal performance. Furthermore, we show that this low-complexity policy converges to the optimal policy for the infinite case as the number N of processes increases.

Furthermore, we studied quickest detection under arbitrarily distributed busy and idle times, in particular, heavy-tail distributions. For heavy-tailed busy time, we show that the persistency property of heavy-tail distributions makes it particularly important to adopt a switching strategy (rather than waiting faithfully in one process) to avoid realizations of exceptionally long busy periods.

2 Opportunity Tracking and Exploitation

2.1 Robust Opportunity Tracking under Imperfect Sensing

We have investigated opportunity tracking and exploitation in multiple channels when spectrum sensing is subject to error. We have formulated the problem as a restless multi-armed bandit process, which is, in general, PSAPCE-hard. Surprisingly, we have shown in [4–7] that for this class of restless bandit process most relevant to cognitive radio systems, simple structural policies exist that achieve a strong performance with low complexity. Specifically, we show that the myopic policy, which maximizes the expected immediate reward while ignoring the impact of the current action on the future, has a simple structure when the false alarm probability of the channel state detector is below a certain value. This structure is semi-universal: it is independent of the Markovian transition probabilities that govern the stochastic behavior of the primary users. The myopic policy can thus be implemented with minimal prior knowledge on the primary system, and it automatically tracks model variations of the primary system. Furthermore, we show that with such a simple and robust structure, the myopic policy achieves the optimal performance for the two-channel case. Numerical examples suggest its optimality for the general case.

To analytically characterize the performance of the myopic policy in the general case, we have developed closed-form lower and upper bounds on the steady-state throughput achieved by the myopic policy. The lower bound monotonically approaches to the upper bound as the number of channels increases. This result thus defines the limiting performance of the myopic policy as the number of channels approaches to infinity. Furthermore, by analyzing a genie-aided system which provides an upper bound on the optimal performance, we have characterized the approximation factor of the myopic policy to bound the worst-case performance loss of the myopic policy with respect to the optimal policy.

2.2 Opportunistic Spectrum Access in Self Similar Primary Traffic

We have also investigated opportunity tracking and exploitation in self-similar primary traffic with long range dependency.

In [8], we have investigated MAC protocols for tracking spectrum opportunities in self-similar primary traffic over multiple channels. We adopt a multiple time scale hierarchical Markovian model of self-similar traffic and develop a decision-theoretic framework based on the theory of POMDP for opportunity tracking and exploitation in self-similar primary traffic. Unfortunately, solving a general POMDP is often intractable due to the exponential complexity. A simple approach is to implement the myopic policy, which only focuses on maximizing the immediate reward and ignores the impact of current action on the future reward. We have shown in [8] that the myopic policy has a simple and robust structure under certain conditions. This simple structure obviates the need to know the transition probabilities of the underlying multiple time scale Markovian model and allows automatic tracking of variations in the primary traffic model. Compared to Markovian channel models, the model at hand is more general but requires more parameters, it is thus more important to have policies that are robust to model mismatch and parameter variations. The strong performance of the myopic policy with such a simple and robust structure has been demonstrated through extensive simulation examples.

2.3 Opportunistic Spectrum Access in Asynchronous Unslotted Primary Systems

We have also investigated Opportunistic Spectrum Access (OSA) in unslotted primary systems. The occupancy of each channel by primary users is modeled as a continuous-time Markov chain, which has been shown to match well with the spectrum usage in wireless LAN. The secondary network adopts a slotted transmission structure. At the beginning of each slot, a secondary user decides which channel to sense and potentially transmit over. The problem appears to be significantly more complex than its counterpart in slotted primary systems due to the arbitrary starting and ending times of the primary transmissions and the half duplex mode of the secondary user that prevents it from sensing the channel during a transmission.

In [9], we have established a certain equivalence between OSA in unslotted primary systems and that in slotted primary systems. This equivalence points to the possibility of reducing the design of OSA in unslotted primary systems to that in slotted primary systems, a significantly simpler problem. Specifically, it is shown that even though the underlying primary systems are modeled as continuous-time Markov chains, the joint design of OSA fits into the discrete-time constrained POMDP framework that we developed in our prior work for the slotted case. This result is based on the following two key observations: (i) Opportunity detection should be formulated as detecting the channel state during the transmission period of a secondary user's slot based on the measurements taken in the sensing period of the slot; (ii) under this formulation of opportunity detection, the difference between unslotted and slotted primary systems — that transmissions of primary users can start and end at arbitrary time instants — simply contributes to sensing errors.

In [9], we further show that the separation principle that we established in our prior work for OSA in slotted primary systems is preserved for the unslotted case under certain conditions. This result does not follow directly from the separation principle for the slotted case. The main difficulty here is that the operating characteristics (probabilities of false alarm and miss detection) of the optimal spectrum sensor is time varying and dependent on the observation and decision history. This significantly enriches the design space and complicates the analysis of the optimal solution. In [9], we show that when the variation of the false alarm probability with respect to the observation and decision history satisfies certain conditions, the separation principle is preserved; the same simple, robust, and optimal design of OSA can be achieved in unslotted primary systems.

We have also investigated the extension of our previous result on spectrum opportunity tracking to non-Markovian channel occupancy models [10, 11]. In particular, we consider two simple round-robin tracking policies for dynamic multi-channel access in cognitive radio networks one in which channel switching takes place when the primary user is sensed to be present, and one in which a channel switching takes place when the primary user is sensed to be absent. Our prior work has shown that these policies are each optimal under certain conditions when the primary user occupancy on each channel can be described as an independent two-state Markov chain. In [10], we consider a very general case where the primary user occupancy on each channel is an arbitrary stationary and ergodic two-state process, and derive bounds on their performance. The bounds provide insights into conditions under which these extremely simple policies perform well.

3 Cognitive Networking

Under this research topic, we focus on cognitive networking under unknown and dynamic models of the coexisting primary systems. Our technical approaches rest on continuum percolation and stochastic online learning and decision theory.

3.1 Connectivity and Multi-Hop Delay of Cognitive Radio Networks

We have addressed in [12, 13] the connectivity of large-scale ad hoc heterogeneous wireless networks, where secondary users exploit channels temporarily unused by primary users and the existence of a communication link between two secondary users depends not only on the distance between them but also on the transmitting and receiving activities of nearby primary users. We have introduced the concept of connectivity region defined as the set of density pairs – the density of secondary users and that of primary transmitters – under which the secondary network is connected. Using theories and techniques from continuum percolation, we have analytically characterized the connectivity region and revealed the tradeoff between proximity (the number of neighbors) and the occurrence of spectrum opportunity. Specifically, we have shown three basic properties of the connectivity region – contiguousness, monotonicity of the boundary, and uniqueness of infinite connected components, where the uniqueness implies the occurrence of a phase transition phenomenon in terms of the almost sure existence of either zero or one infinite connected component; we have identified and analyzed two critical densities which jointly specify the profile as well as an outer bound of the connectivity region; we have studied the impacts of secondary users' transmission power on the connectivity region and the conditional average degree of a secondary user, and designed the transmission power of secondary users to maximize the tolerance of the primary traffic load. Furthermore, we have established a necessary and a sufficient condition for connectivity. The necessary condition which depends on the conditional average degree of a secondary user gives another outer bound of the connectivity region, while the sufficient condition leads to an inner bound of the connectivity region.

We further study the impact of temporal dynamics of the primary traffic on the connectivity and delay scaling of the secondary networks. In [14], we consider a Poisson distributed secondary network overlaid with a Poisson distributed primary network in an infinite two-dimensional Euclidean space1. The existence of a communication link between two secondary users depends on not only their separation but also the occurrence of the spectrum opportunity determined by the transmitting and receiving activities of nearby primary users. We define connectivity via the finiteness of the minimum multihop delay (MMD) between two randomly chosen secondary users. Using theories and techniques from continuum percolation and ergodicity, we analytically characterize the connectivity of the secondary network defined in terms of the almost sure finiteness of the multihop delay, and show the occurrence of a phase transition phenomenon while studying the impact of the temporal dynamics of the primary traffic on the connectivity of the secondary network. Specifically, as long as the primary traffic has some temporal dynamics caused by either mobility and/or changes in traffic load and pattern, the connectivity of the secondary network depends solely on its own density and is independent of the primary traffic; otherwise the connectivity of the secondary network requires putting a density-dependent cap on the primary traffic load. We show that the scaling behavior of the multihop delay depends critically on whether or not the secondary network is instantaneously connected. In particular, we establish the scaling law of the minimum multihop delay with respect to the source-destination distance when the propagation delay is negligible.

3.2 Online Learning for Distributed Spectrum Sharing under Unknown Models

In a distributed secondary network without a central controller or a dedicated control channel, each secondary user needs to balance choosing the most promising channel with avoiding competing users without knowing others' actions and without assuming any prior knowledge about the primary channel occupancy. We have mathematically formulated this problem as a decentralized multiarmed bandit process (MAB) [15], which is a generalization of the classic MAB that considers a single user studied in the seminar paper by Lai and Robbins in 1985. Specifically, we showed in [15] that the minimum regret (where the regret is defined as the total performance loss with respect to the ideal case with known model and perfect centralized scheduling) in the decentralized MAB grows at the same logarithmic order as in the centralized counterpart considered by Lai and Robbins. We also developed a Time Division Fair Sharing (TDFS) framework for constructing order-optimal and fair decentralized policies.

We then further extended this result in three directions. First, the result in [15] is obtained under the assumption that the primary traffic is i.i.d. over time. We have relaxed this assumption by considering a more general Markov model (with unknown transition probabilities) of the primary traffic. Second, the result in [15] assumes perfect sensing at the secondary users. We have extended the result to handle sensing errors. Third, the result in [15] assumes a slotted primary system.

Specifically, in [16–18], the occupancy of each channel is modeled as a Markov chain with unknown transition probabilities. Multiple distributed secondary users aim to learn the primary traffic model and exploit the idle slots for transmission. The objective of the secondary user is to maximize the long-term throughput by designing an optimal channel selection policy without knowing the traffic dynamics of the primary users and without centralized scheduling among secondary users. We show in [16–18] that the problem leads to a restless multi-armed bandit with unknown dynamics, a significant variation of the multi-armed bandit problems that has not been studied in the literature. We have constructed a channel sensing and access policy that achieves a regret with logarithmic order when an arbitrary nontrivial bound on certain system parameters is known. When no knowledge about the system is available, we extend the policy to achieve a regret arbitrarily close to the logarithmic order. In both cases, the throughput of the secondary network achieves the maximum value defined by the ideal scenario where the secondary network with N users knows which N channels are the best and always access these N channels through a perfect centralized scheduling that eliminates collisions.

In [19, 20], we address the issue of sensing errors and their effect on the learning ability of the secondary users. We show in [19, 20] that with multiple distributed secondary users, imperfect sensing significantly complicates the problem. The main difficulty is that each secondary user cannot distinguish between secondary collisions caused by competition and primary collisions caused by sensing errors. A failed transmission due to secondary collisions does not reflect the channel quality. If a secondary user learns the channel quality from the history of successful transmissions, the best channels may not be correctly identified. In other words, collision among secondary users affects not only the immediate reward but also the learning ability at each colliding user, which further degrades the system long-term throughput. In [19, 20], we formulate the multi-user DSA with imperfect sensing as a variant of decentralized MAB with multiple players to take into account the imperfect reward observation. We show that the optimal system regret has the same logarithmic order as in the case with perfect sensing. A decentralized SLCD (Synchronized Learning under Corrupted Data) policy is proposed to achieve the logarithmic order of the system regret. Under this policy, the network throughput converges to the same maximum throughput as in the ideal case with known model, centralized scheduling, and perfect sensing.

In [21], we address multi-channel opportunistic spectrum access in *unslotted* primary systems under known mdoels. The primary occupancy of each channel is modeled as a general on-off renewal process. The distributions of the busy and idle times and the utilization factors of all channels are unknown to the secondary user. The objective of the secondary user is to identify and exploit the best channel (i.e., the channel with the least primary traffic) through efficient online learning. We have developed a dynamic channel access policy that achieves the throughput offered by the best channel under certain mild conditions on the busy/idle time distributions. More specifically, the cost associated with learning the unknown channel occupancy models over a horizon of length T diminishes at the rate of $\log T/T$. The policy is obtained by constructing a hypothetical multi-armed bandit with virtual reward which, while not directly reflecting throughput, preserves the ranking of the channels in terms of throughput.

3.3 Multichannel Estimation for Opportunistic Spectrum Access

In [22, 23], we address the problem of estimating the parameters of the primary traffic in multiple channels under a constraint on the total sensing time. An accurate stochastic modeling of the primary system channel occupancy plays a crucial role in designing the optimal algorithms for sensing, tracking, and exploiting spectrum opportunities. However, such a model may not be known a priori and must be learned through sensing under a constraint on the total amount of sensing time. In [22,23], the primary traffic in each channel is modeled as a continuous Markov on-off process. The objective is to learn the parameters of each channel under a constraint on the total sensing time with the performance measured by the total mean square error (MSE) across all channels.

In [22, 23], We obtain the Fisher information matrix and the maximum likelihood estimator in closed form. Given that the optimal allocation of the total sensing time to multiple channels depends on the unknown parameters, we propose a sequential estimation strategy which dynamically adjusts the allocation of sensing time based on the partial learning results obtained up to the current time. Specifically, the proposed sequential estimation policy operates under an epoch structure. Within each epoch, channels are sensed in turn, each for a fraction of the epoch length with the fraction determined based on the current estimate of the channel parameters. The epoch length grows over time to take advantage of the increasing accuracy of the estimates. We show in [22, 23] that the proposed sequential estimator is asymptotically efficient, i.e., it achieves the Cramer-Rao Bound (CRB) as the total sensing time grows.

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